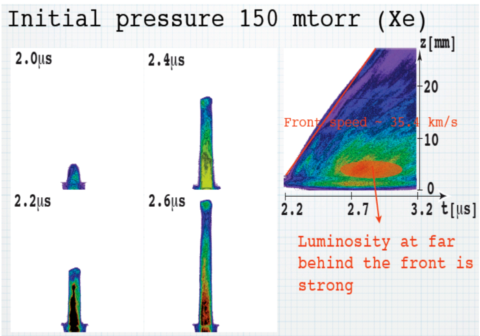
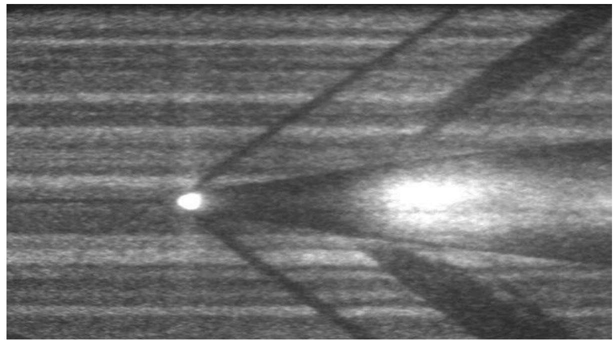
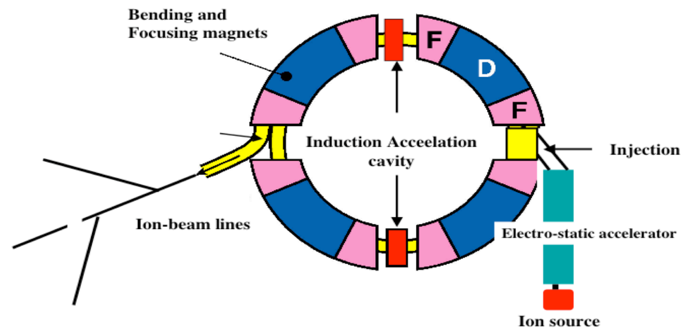
High-Energy-Density Experiments in Japan







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Department of Energy Sciences, Tokyo Institute of Technology[a],

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High Energy Accelerator Research Organization[d] KEK, Tsuykuba

High Energy Density Experiments in Japan

- Pulse Power based HED Experiments (TIT)

- Beam Plasma Interaction Experiments using Foil Explosion and Shock Heated Plasma Target (TIT) (Oguri, Hasegawa)
- Beam Physics Issues in Final Transport for HED and/or HIF (UU, TIT, KEK) (Kawata, Kikuchi, Takayama)
- Induction Synchrotron for WD Studies (KEK, TIT, UU) (Takayama)

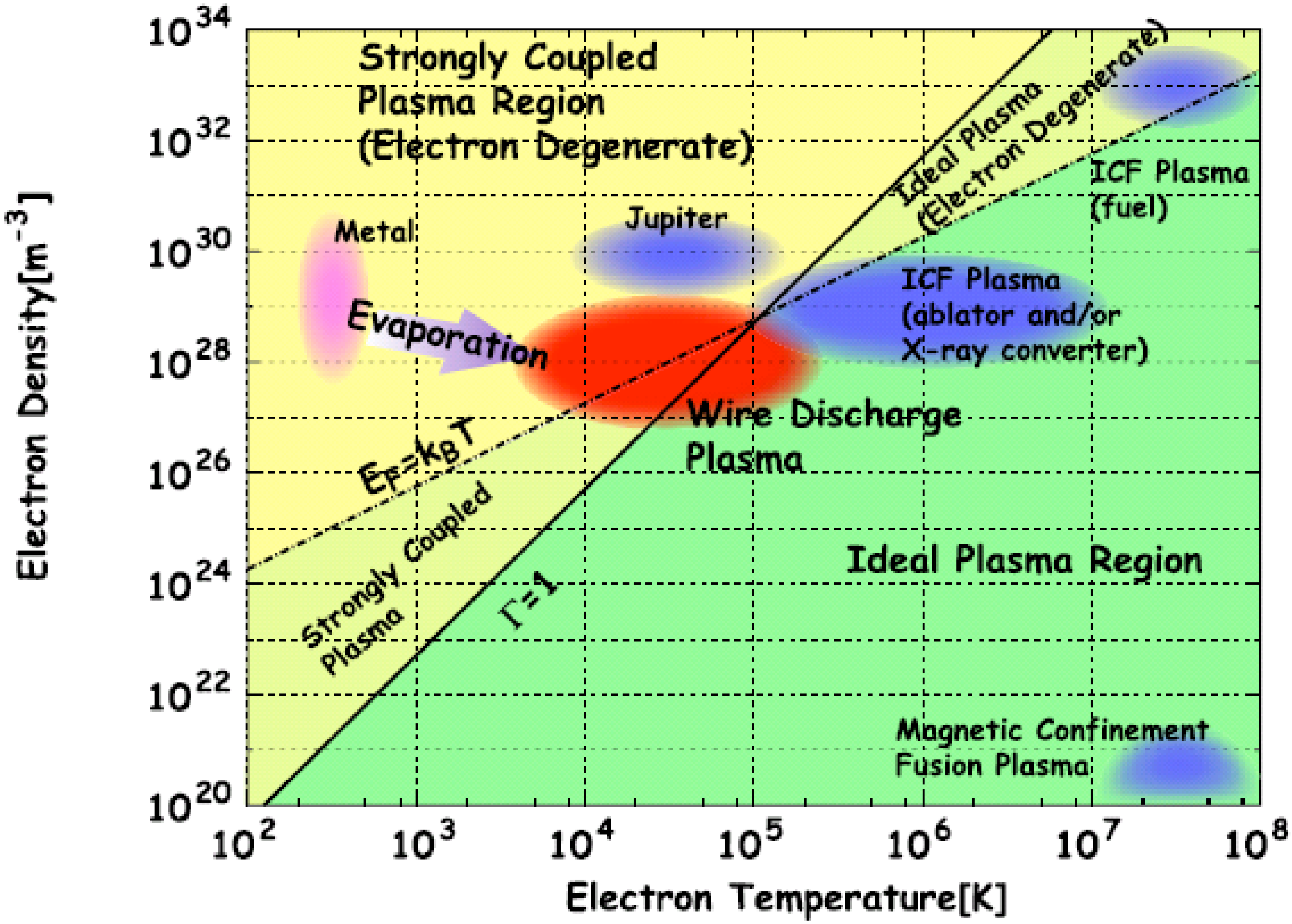
- HED Studies using Intense Laser Irradiation
- (UEC, ILE, UU, UT, JAEA, CRIEPI-TIT) (Yoneda)

  - ***TIT:*** ***Tokyo Institute of Technology***
  - ***KEK:*** ***High Energy Accelerator Organization***
  - ***UU:*** ***Utsunomiya University***
  - ***ILE:*** ***Institute of Laser Engineering, Osaka University***
  - ***UEC:*** ***The University of Electro-Communications***
  - ***JAEA:*** ***Japan Atomic Energy Agency***
  - ***UT:*** ***University of Tokyo***
  - ***CRIEPI*** ***Central Research Institute of Electric Power Industry***

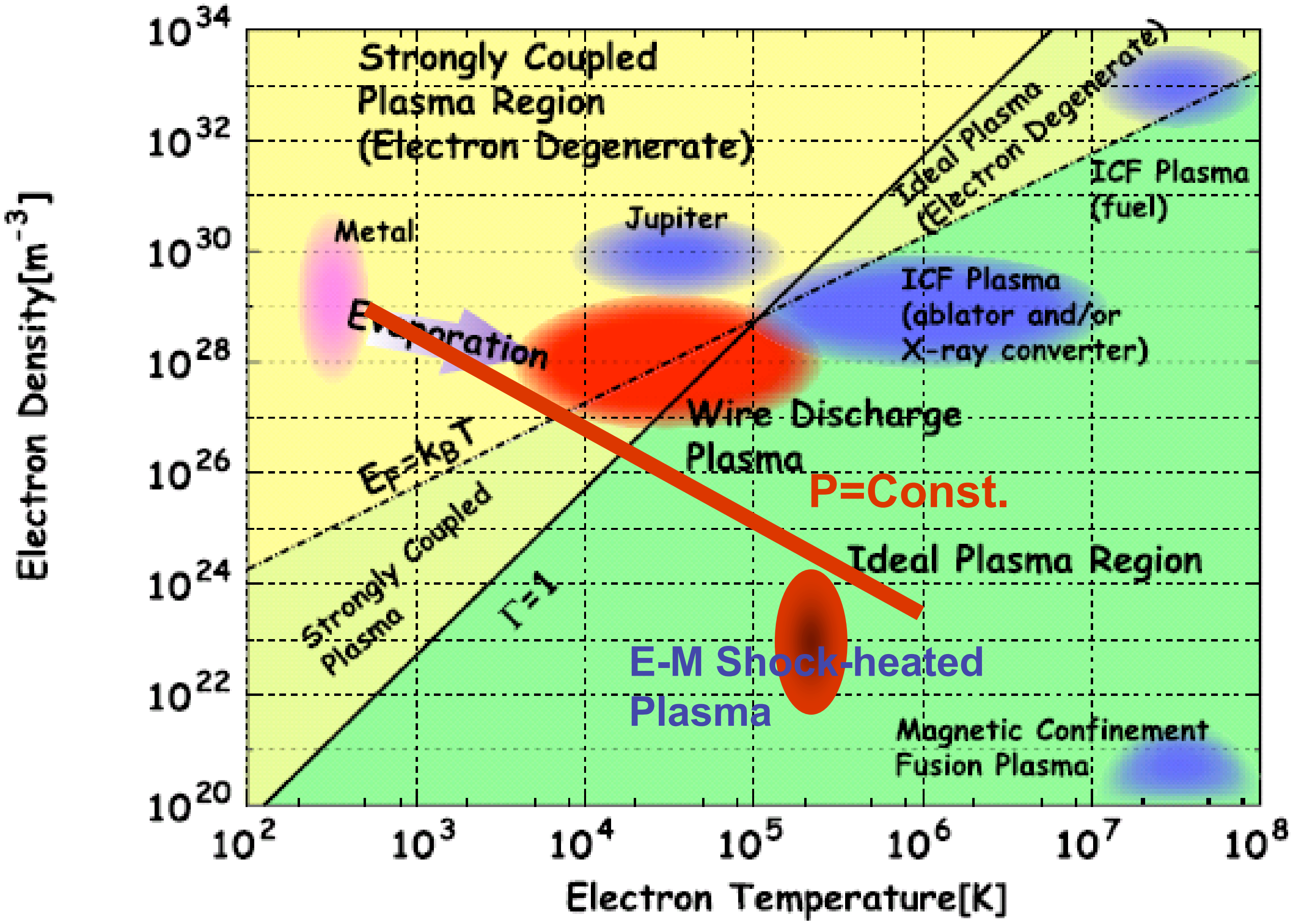
Outline

- Pulse-power-driven HED Physics
  - Dense plasma made by exploding wire discharges in water
  - High temperature plasma in electromagnetically driven strong shock waves for radiation hydrodynamics
- Accelerator based HED Physics
  - Ion beam driver for HED physics
  - Achievable parameter region by induction synchrotron
- Comparison of them

Materials in Density-temperature Diagram

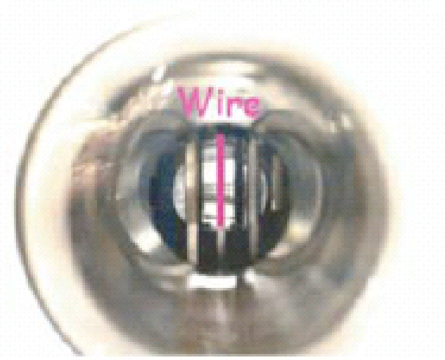


Achievable Parameter Region of Pulse Power Drivers

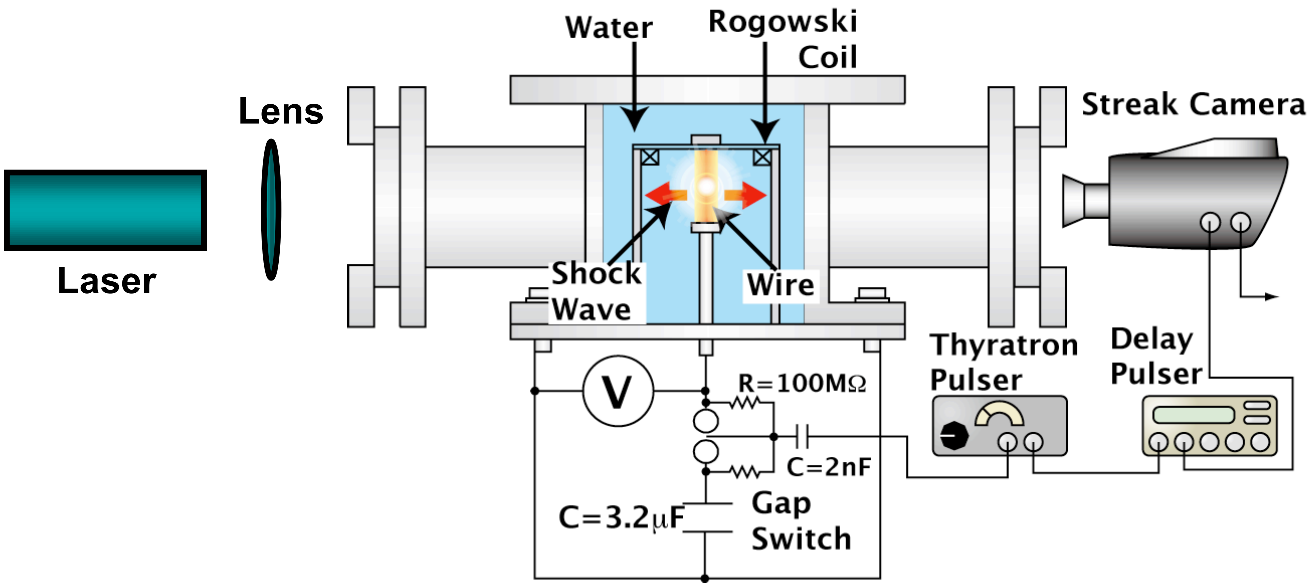


Dense Plasma

Warm-dense Matter Studies using Pulse-powered Exploding Wire Plasma in Water

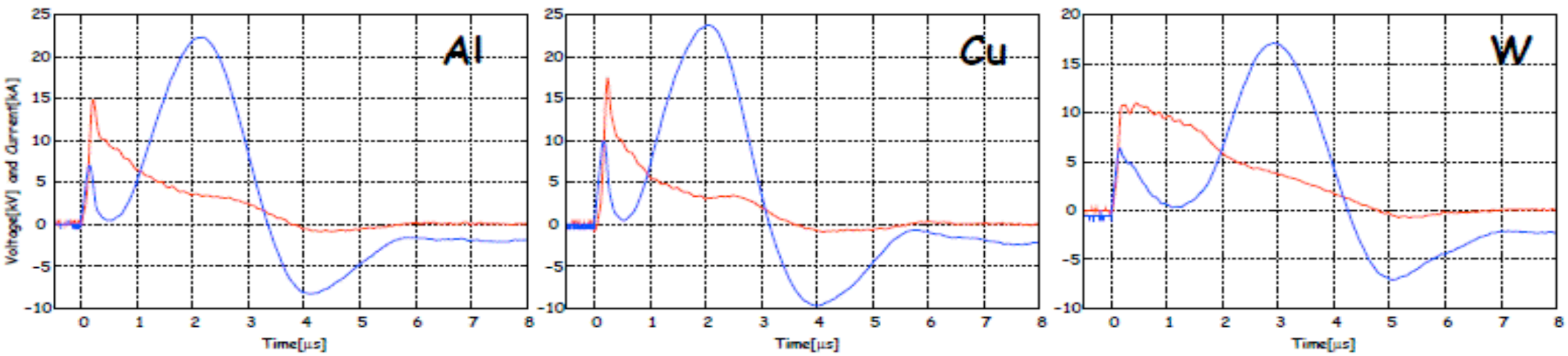


Picture of Load Section



+ Axial symmetry
+ Direct measurements
+ Tamper effect
+ Transparent
- Energy density
- EOS of Water

Electrical conductivity can be directly estimated from reproducible Voltage-Current traces

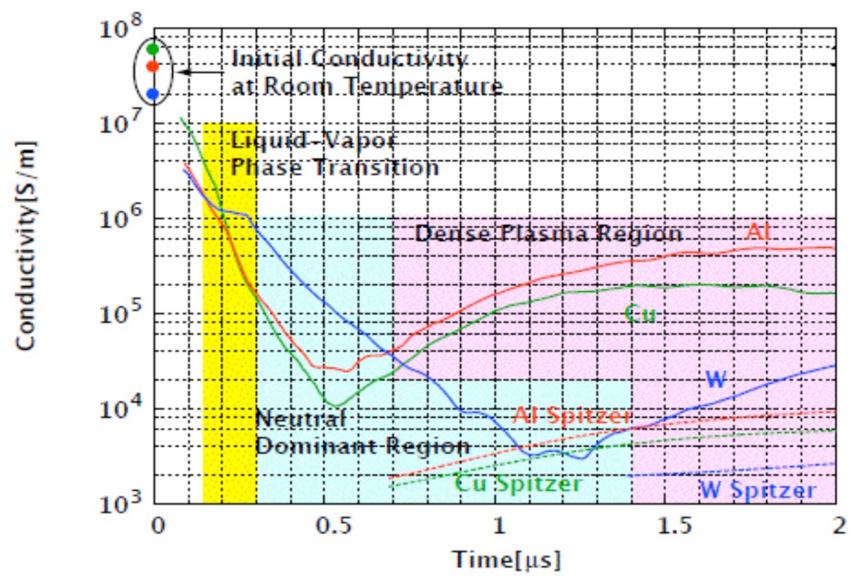


Typical Traces of Voltage and Current

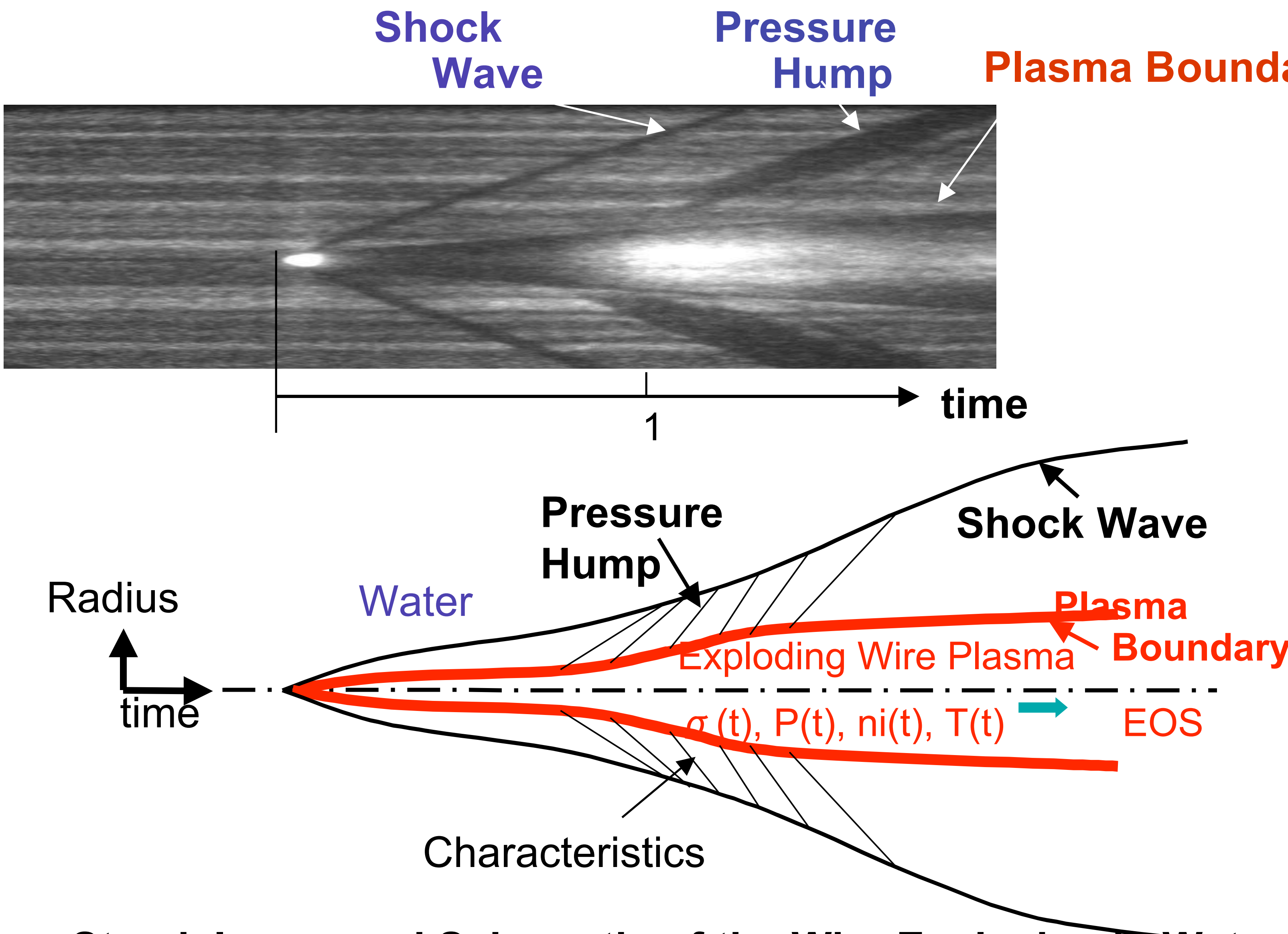
Voltage

Current

Electrical Conductivities



Semi-empirical fitting of hydrodynamic behavior brings us EOS information

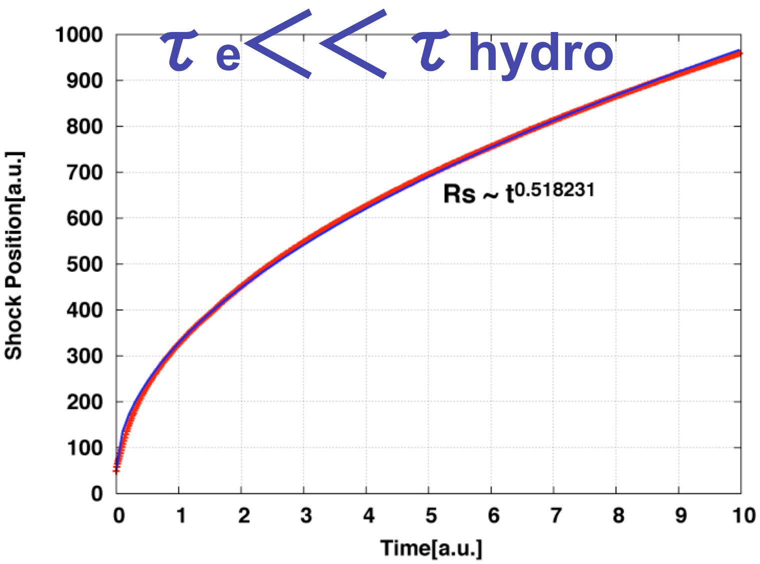


Streak Image and Schematic of the Wire Explosion in Water

Hydrodynamics of cylindrically exploding plasma

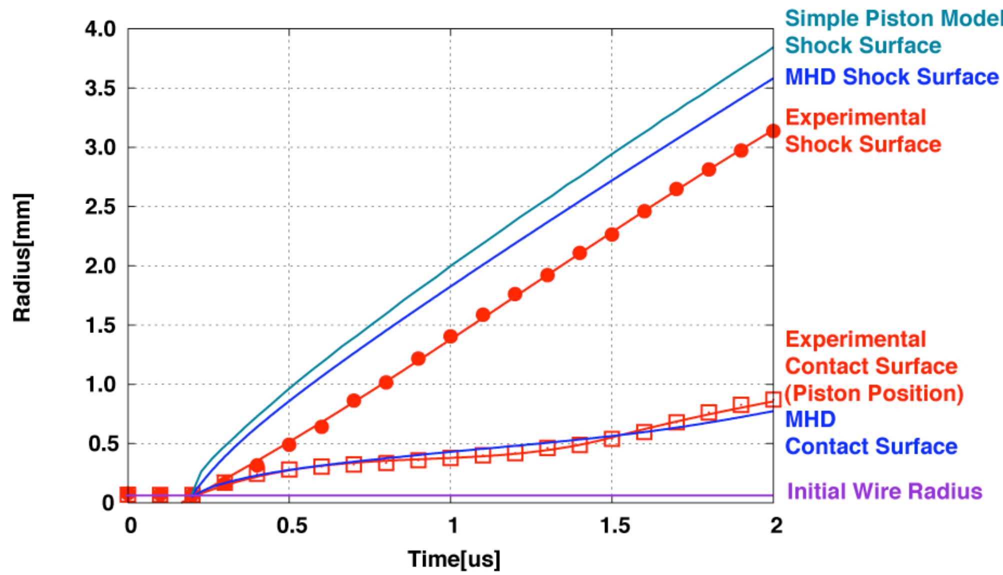
Sedov's solution

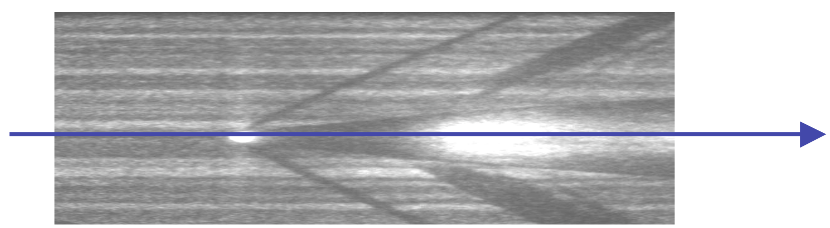
$\tau_e \ll \tau_{hydro}$



Wire explosion

$\tau_e \sim \tau_{hydro}$





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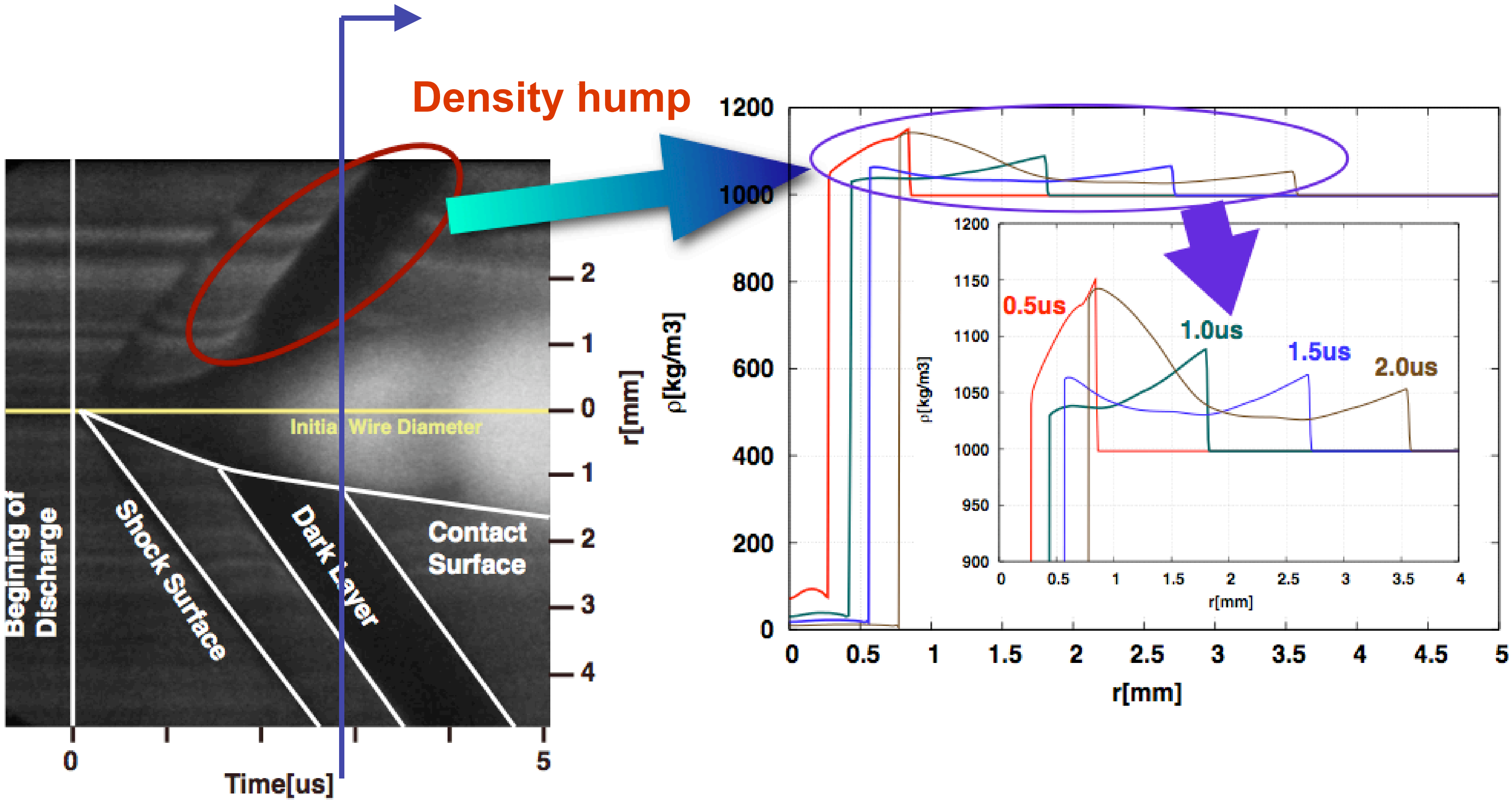
MHD simulation can predict hydrodynamic structure



Semi-empirical fitting of EOS

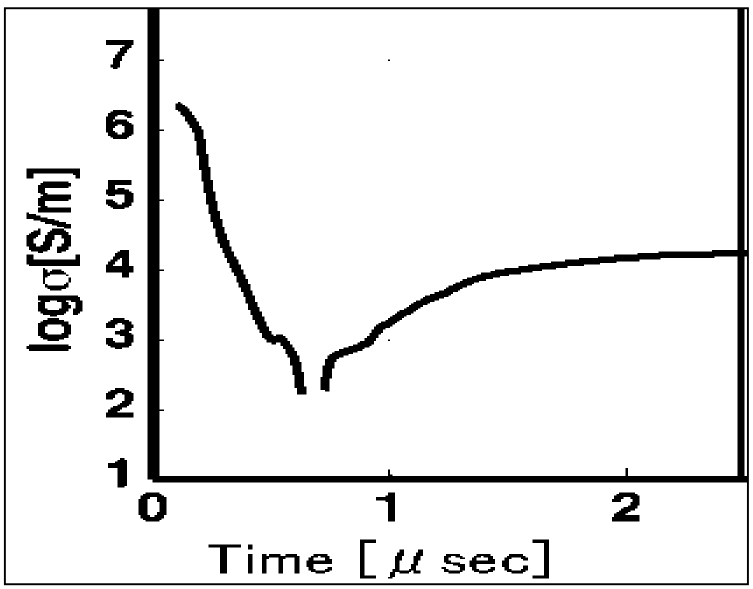
Voltage/Current

Conductivity, Input Power

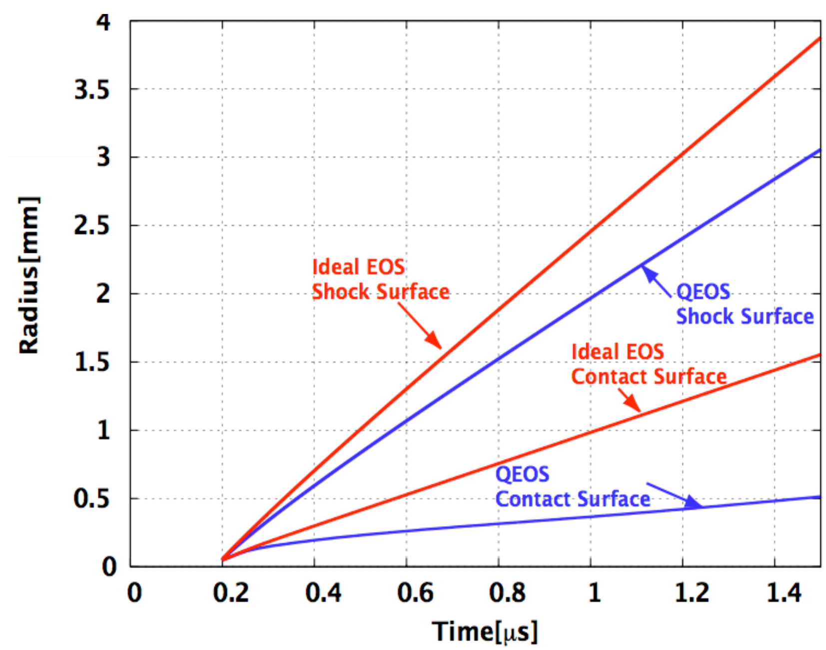
MHD Simulation

Hydrodynamics and Shock evolution

EOS of Plasma and Water



Typical evolution of conductivity

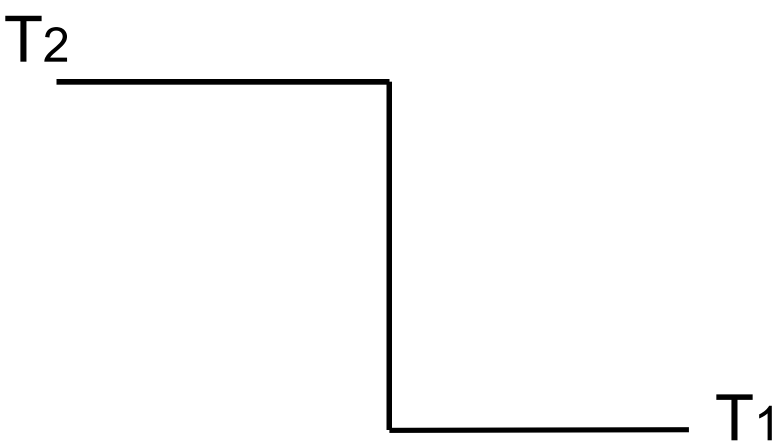


Hydrodynamics of wire-explosion

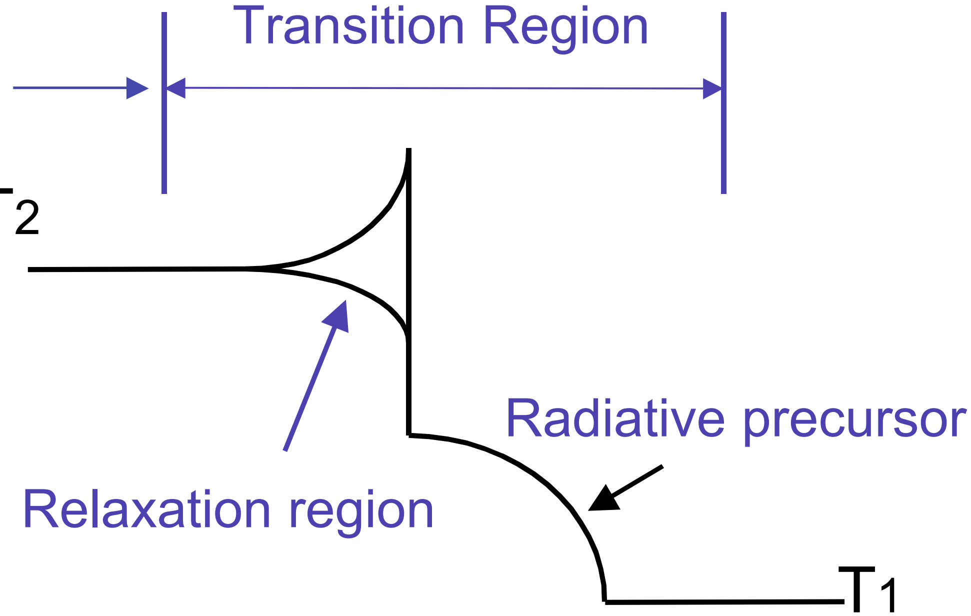
High Temperature Shock Heated Plasma

Formation of Quasi-steady State
1-D Strong Shock Wave

- 1-D assumption enables us to use simplified analytical estimation



Hydrodynamic Shock Wave



Strong Shock Wave

Analytical Criterion for Radiative Shock Wave

- 1-D simplified analytical estimation yields a criterion* of shock speed for radiative regime,

From the requirement of Prad/Pthe > 1

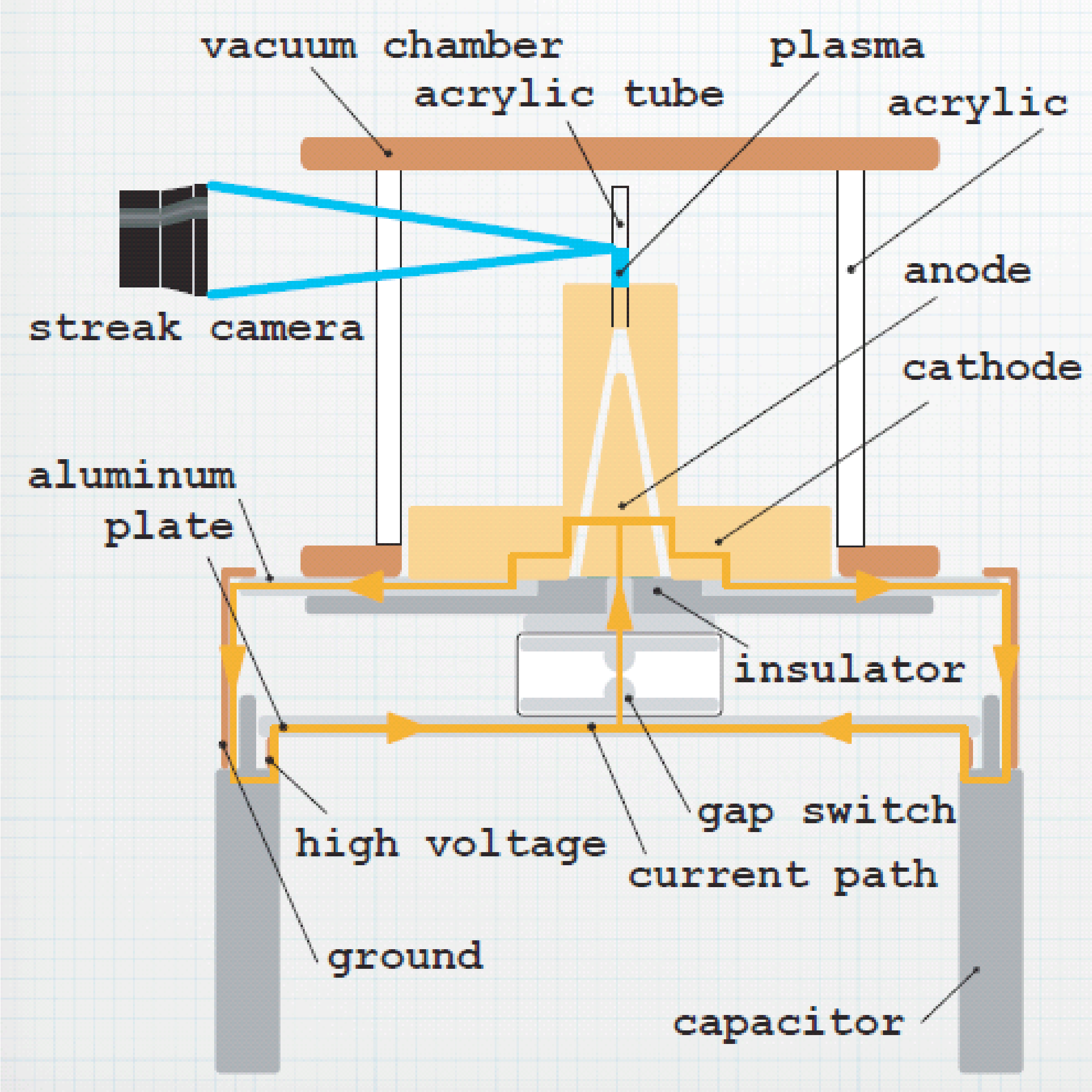
$$D \geq D_{rad} = \left(\frac{7^7 k^4}{72 a} \frac{n_1}{\mu_1^3} \right)^{\frac{1}{6}} \; [m/s]$$

K : Bolzmann's Constant, a: Radiative constant

n1: Particle Density, μ 1 : Particle mass

* S.Bouquet, et.al., Astrophysical J. Supp. 127, 245 (2000)

Experimental Arrangement for the Formation of E-M driven 1-D Strong Shock Wave



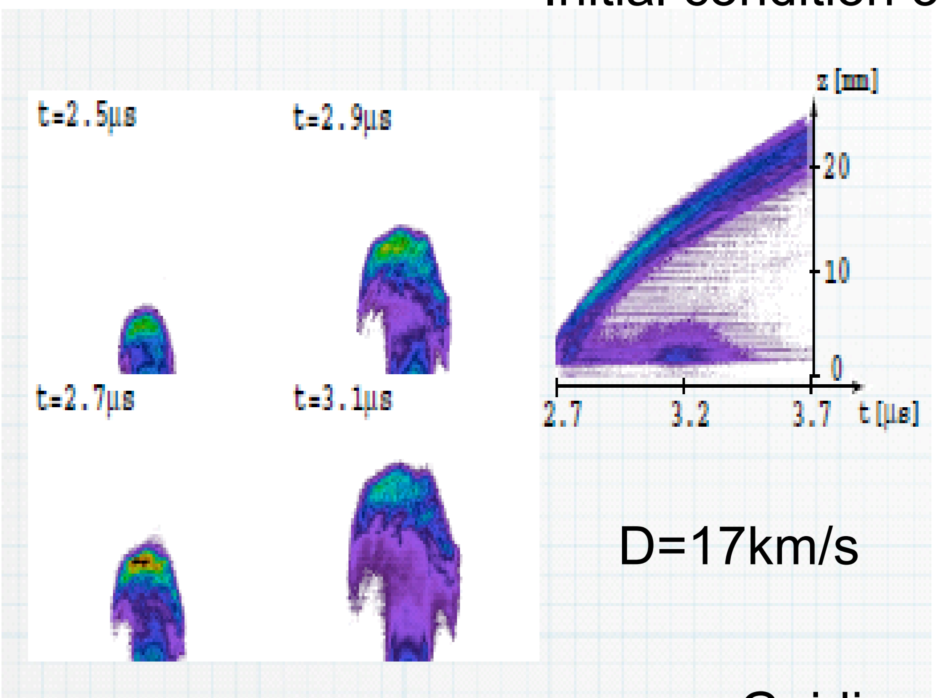
Gases : Xe, Ar

Initial pressure

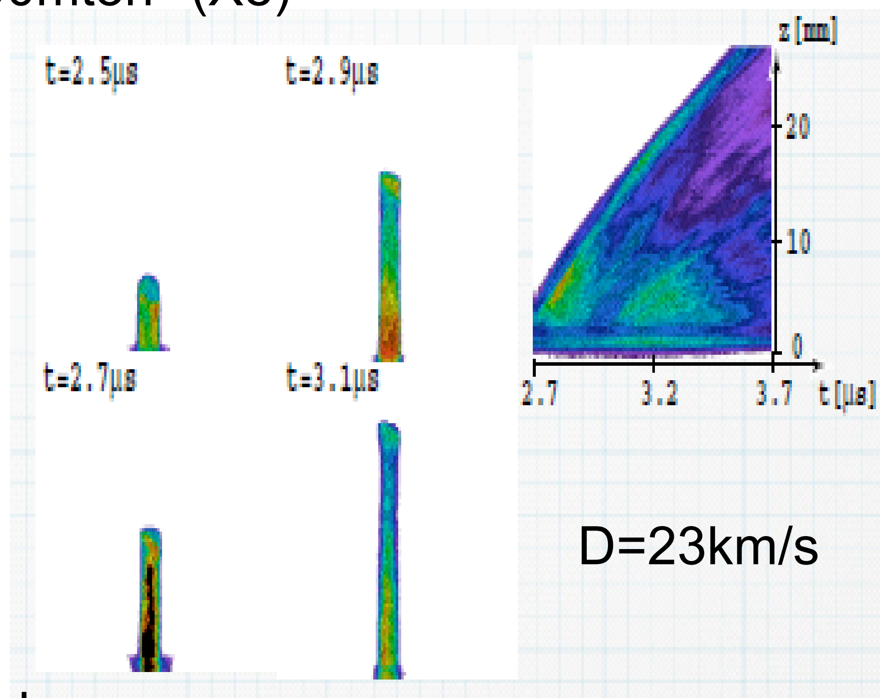
: 50 ~ 8000 mtorr

Quasi-1-D condition was fulfilled by a pair of tapered electrodes and a guiding tube

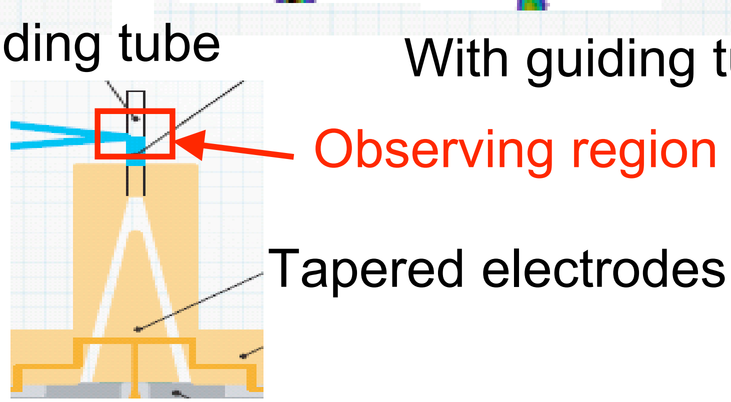
Initial condition 300mtorr (Xe)

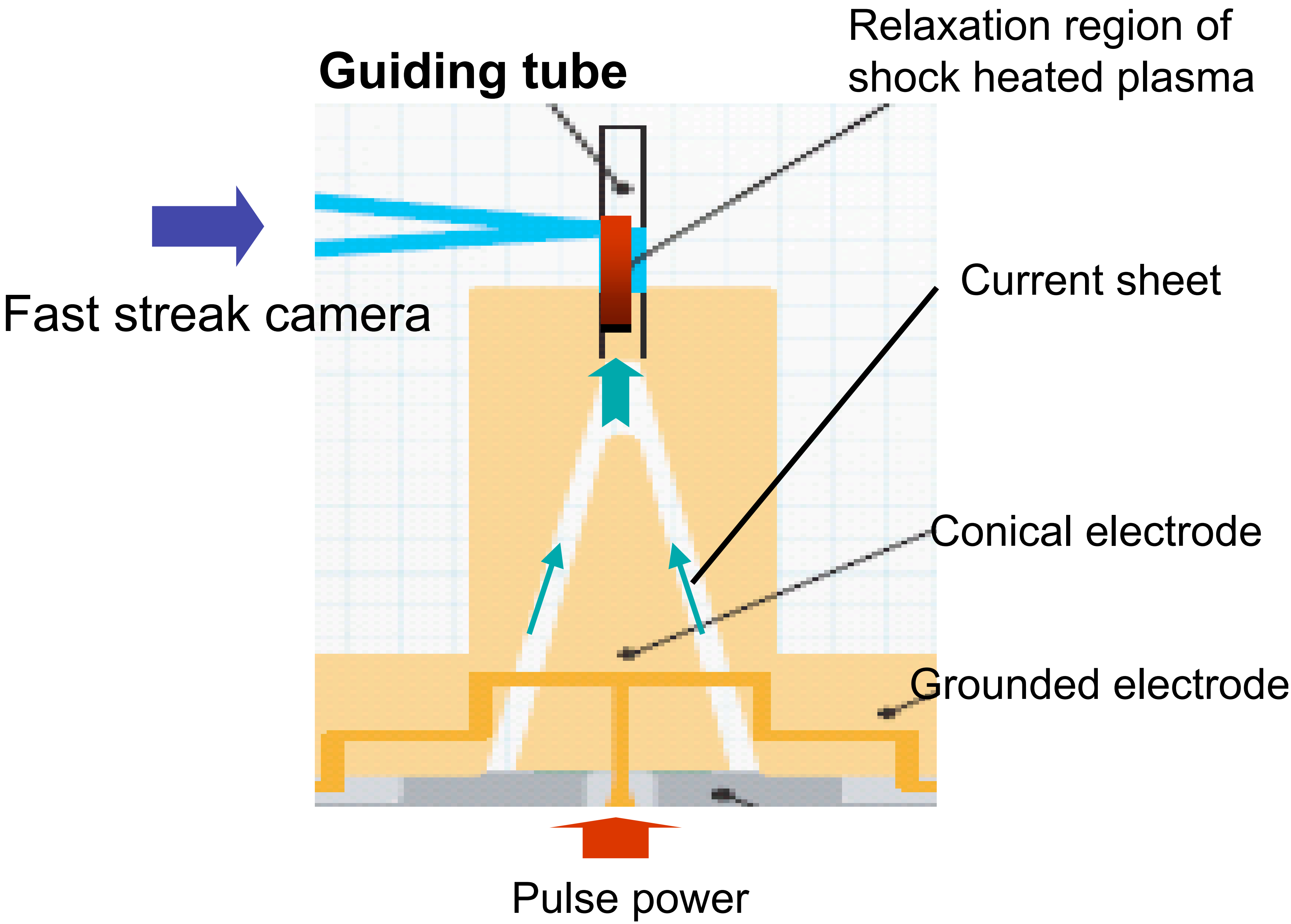


Without guiding tube

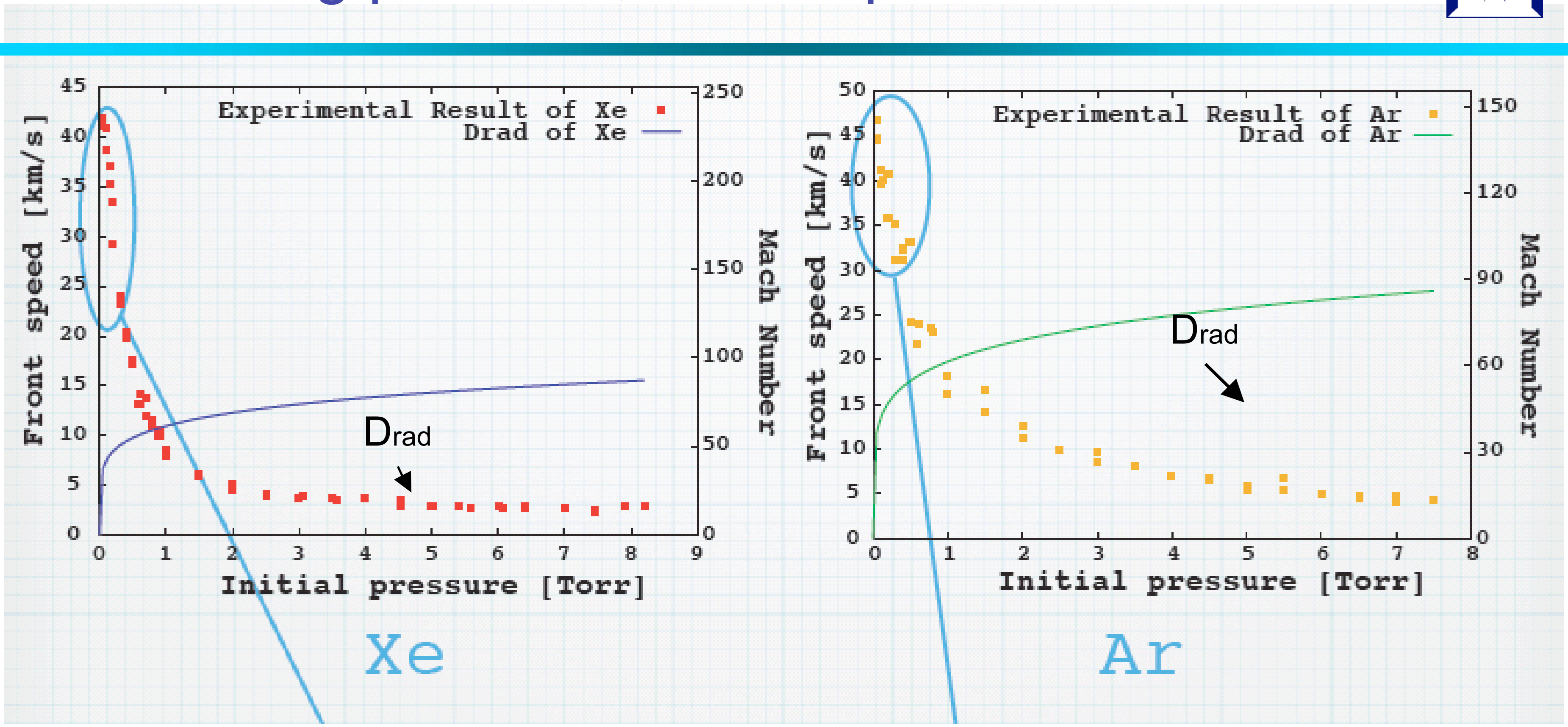


With guiding tube



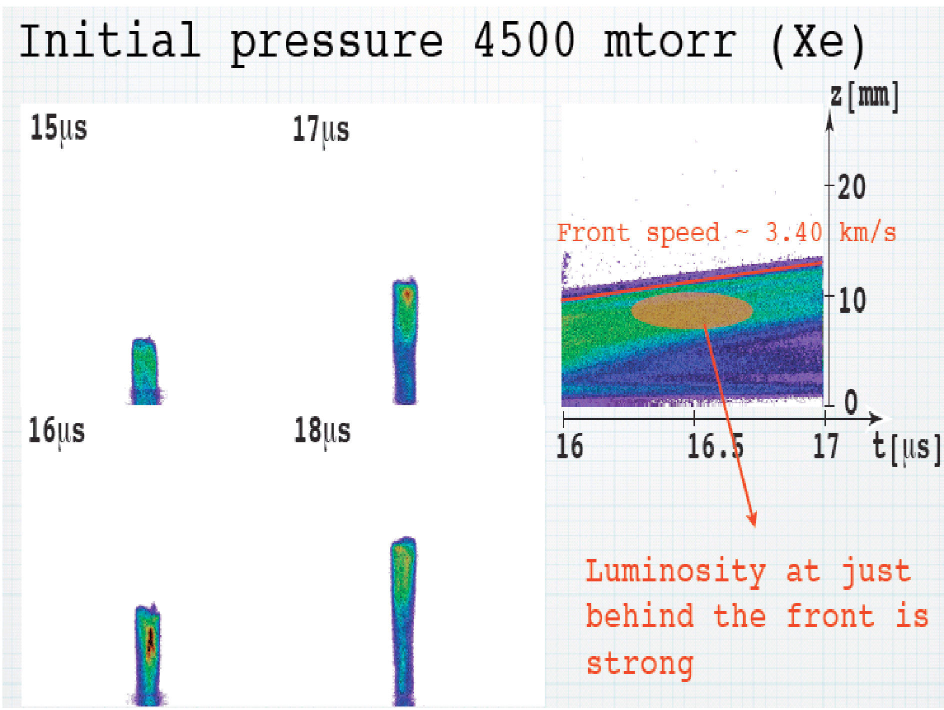

Guiding tube
Relaxation region of
shock heated plasma
Fast streak camera
Current sheet
Conical electrode
Grounded electrode
Pulse power

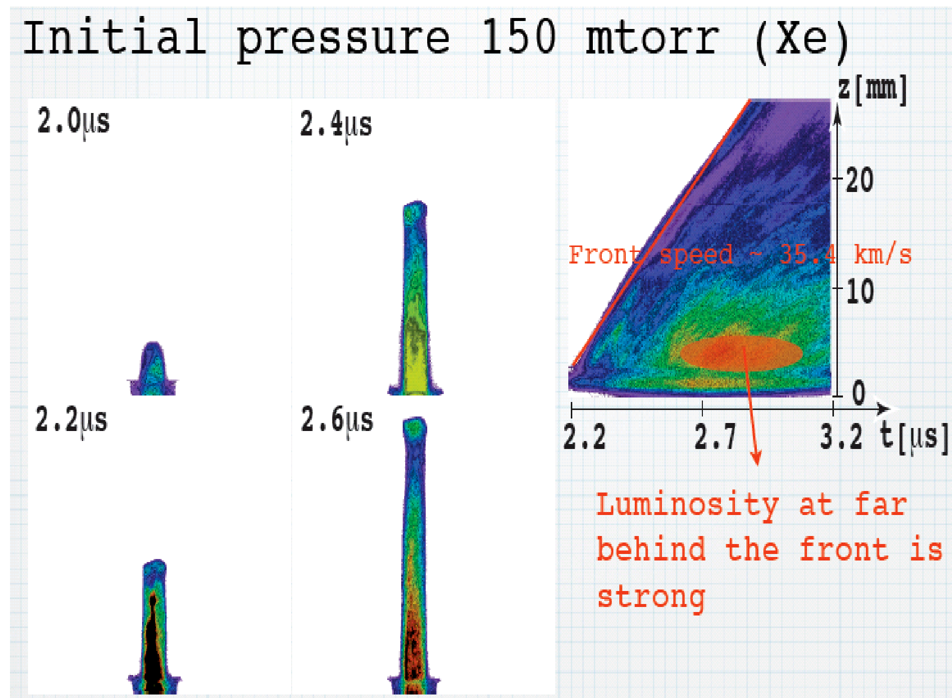
At low filling pressure, shock speed exceeds Drad



Indicating the existence of radiative front in Strong shock waves (M>100)

Typical Images of Fast Framing/Streak Camera





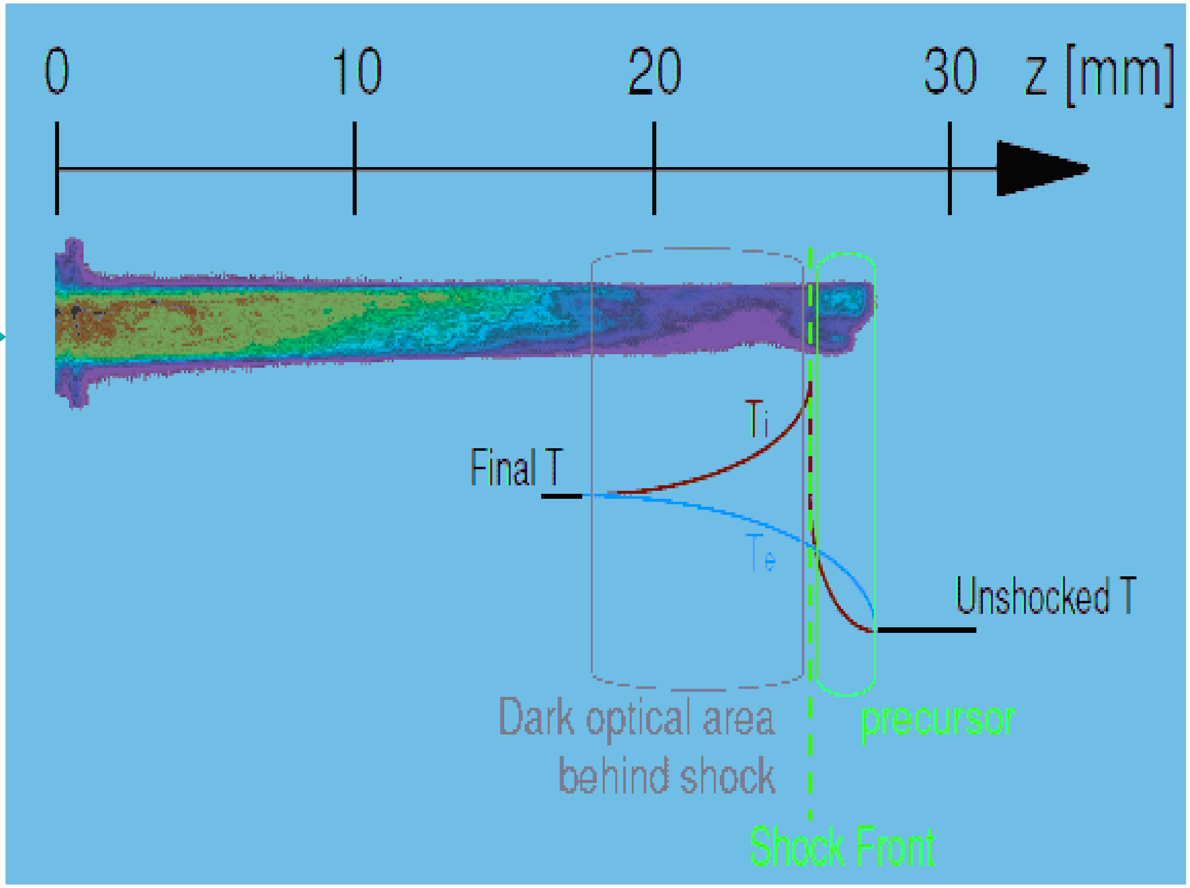
M～20

M～200

Visible image changed with shock strength

Comparison can make clear radiative shock structure

Streak image



Pulse-power-driven Shock Experiments

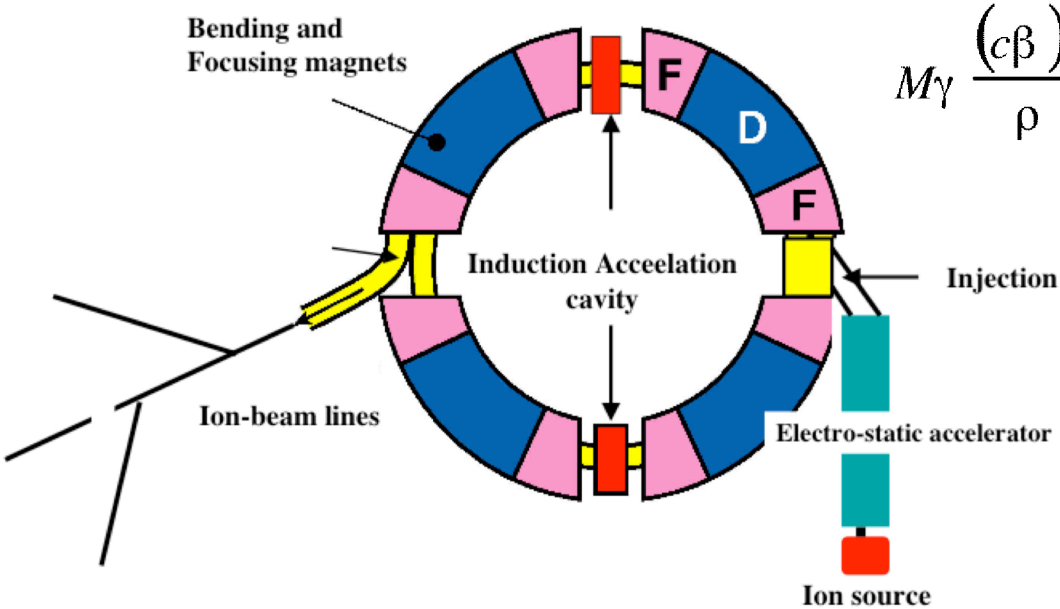
- Quasi-1D strong shock waves can be formed
- Shock Mach number reached 250 under low pressure condition of Xe
- When the front speed exceeded a critical value Drad, the image structure changed
- Results indicates formation of a radiative shock wave

Accelerator Driven well defined Plasma

We can make energetic medium-to-heavy mass ion bunch by induction modulator

All Ion Accelerator

- **Driven by controllable induction modulator**
- **Induction modulator works both for acceleration and confinement**
- **Can accelerate ions with arbitrary masses and charges**
- **Modification of KEK500MeV Booster is planning**



Typical Arrangement of All Ion Accelerator
(K.Takayama et al.,)

Balance Eq.

$$M\gamma\frac{(c\beta)^2}{\rho} = Q\cdot(c\beta)\cdot B \Rightarrow A\cdot m\cdot\gamma\frac{c\beta}{\rho} = Z\cdot e\cdot B$$

Acceleration

$$A\cdot mc^2\cdot\dot{\gamma} = \frac{Z\cdot ec\beta}{C_0}\cdot V_{acc}(t)$$

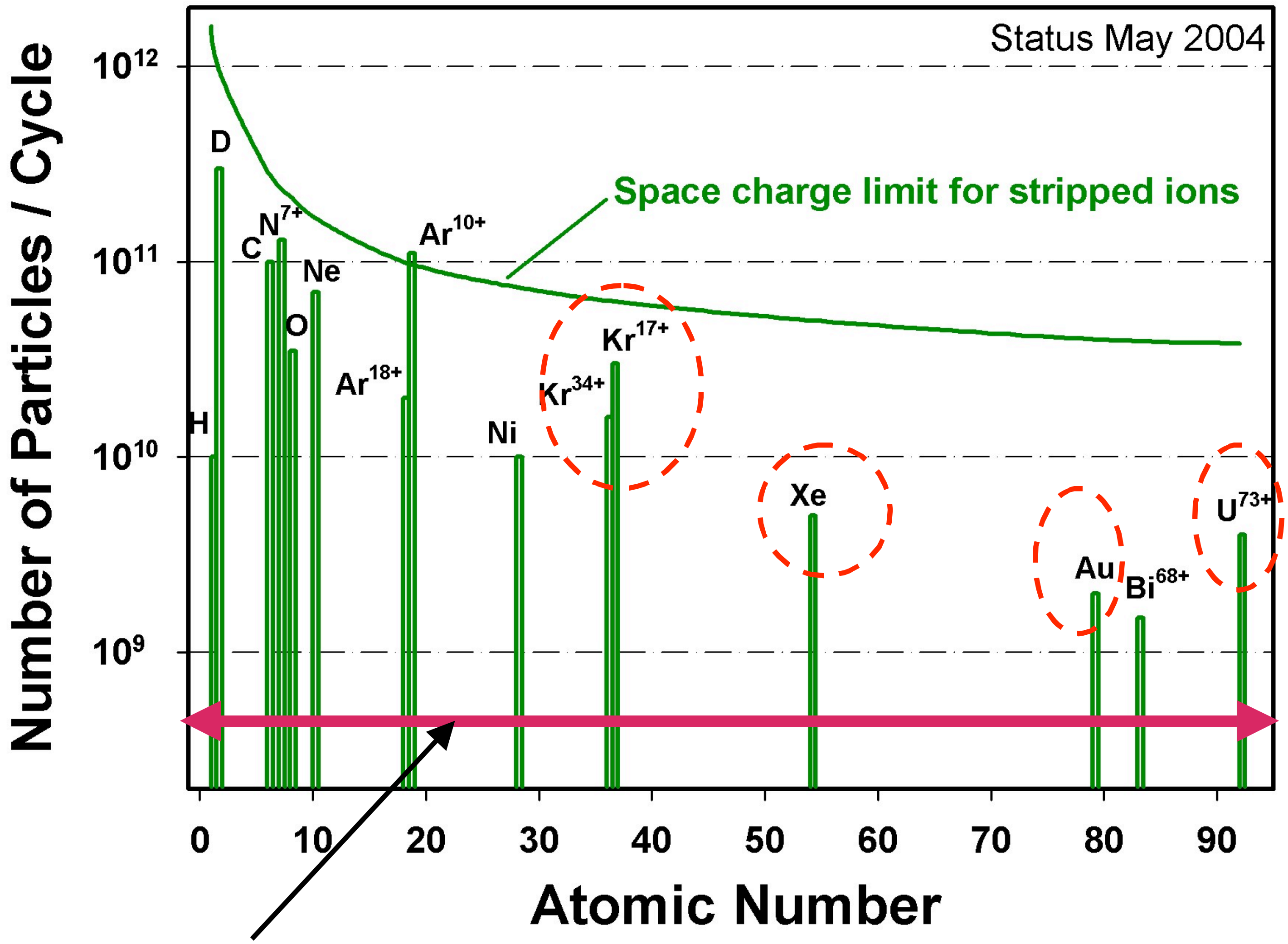
Acceleration Voltage

$$V_{acc}(t) = \rho\cdot C_0\cdot\frac{dB}{dt}$$

Ions available in the existing heavy-ion RF synchrotron (SIS18@GSI)

$C_0 = 216$ m
$f_0 = 214$ kHz
$f = 1$ Hz

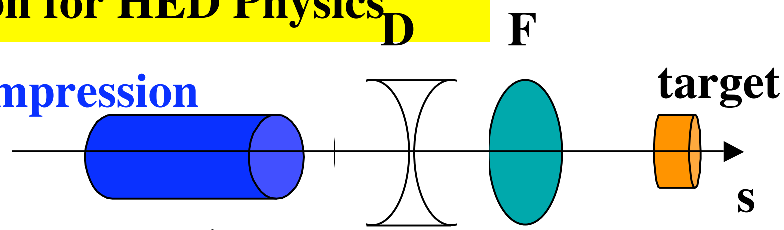
Particle Numbers per SIS18 Cycle



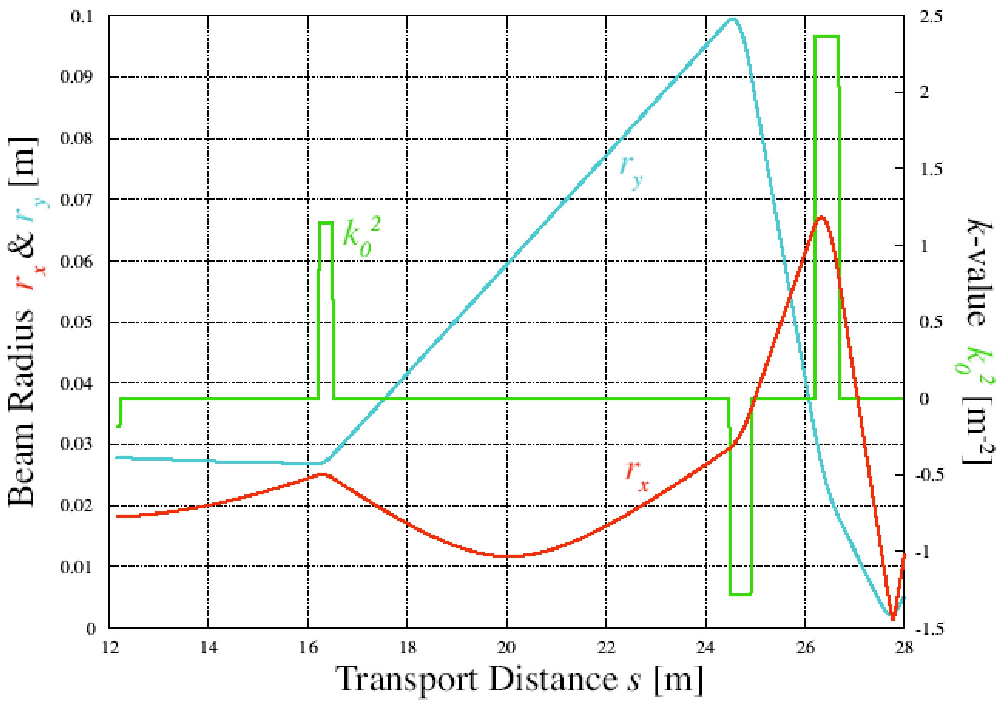
全種イオン加速器ではこの全ての領域をカバーする事を特徴とする。

Beam Compression for HED Physics

a. Transverse Compression (half-mini beta)

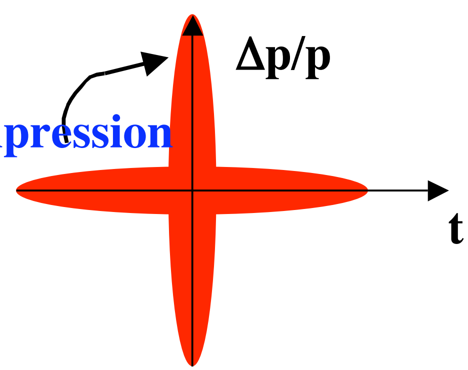


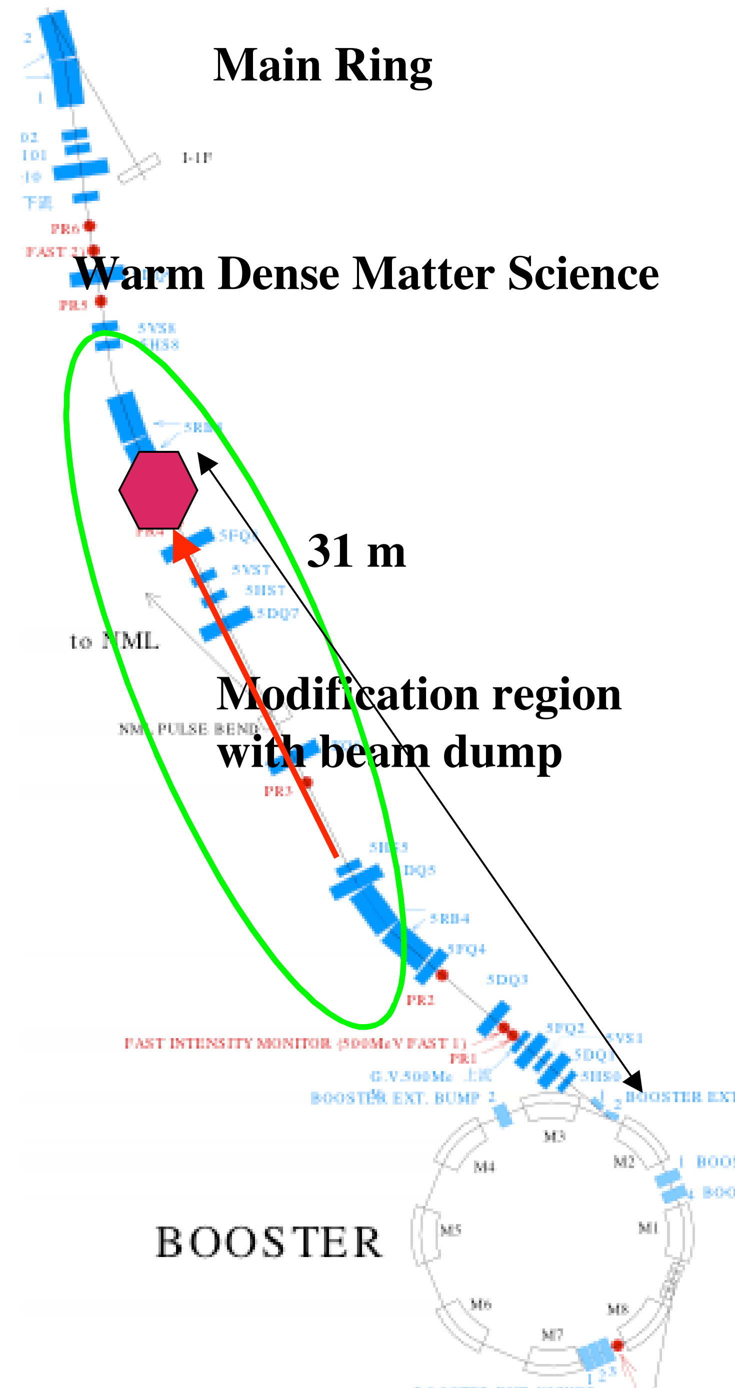
K-value$=k_0^2$



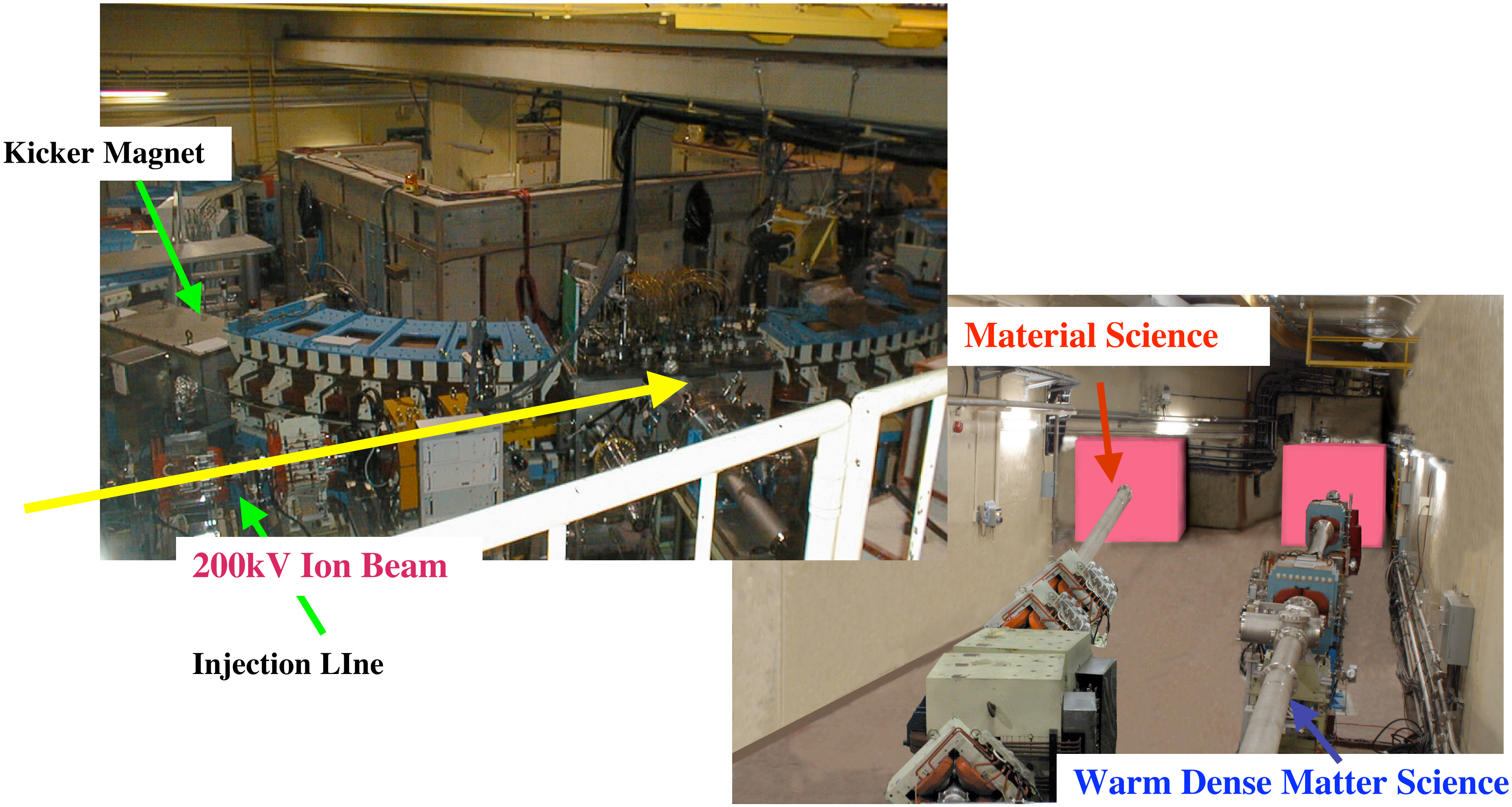
Calculation by T.Kikuchi

b. Longitudinal Beam Compression (RF Rotation)



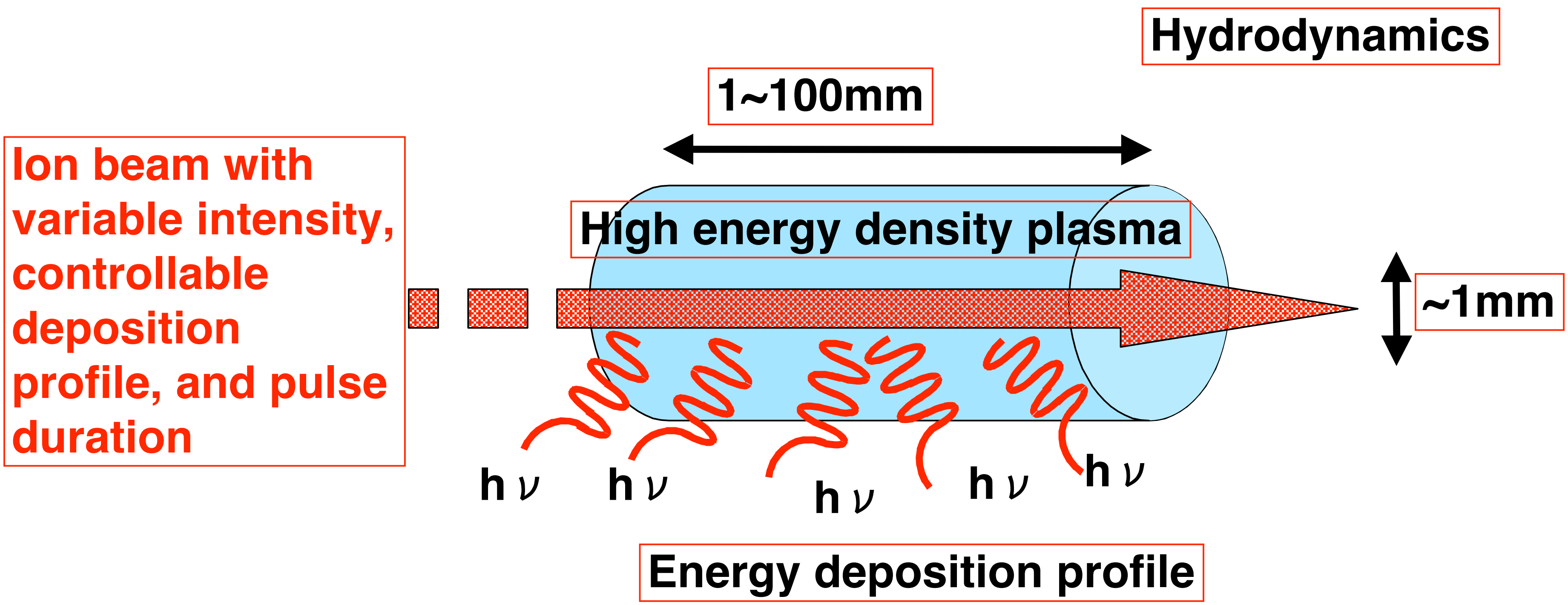


KEK 500MeV Booster and Beam Lines for Beam Applications



Advantages of HIB for HED physics

- Well-defined energy deposition
- Large scale-length and long lifetimes
- Controllability of the deposition profile
- Variable energy density



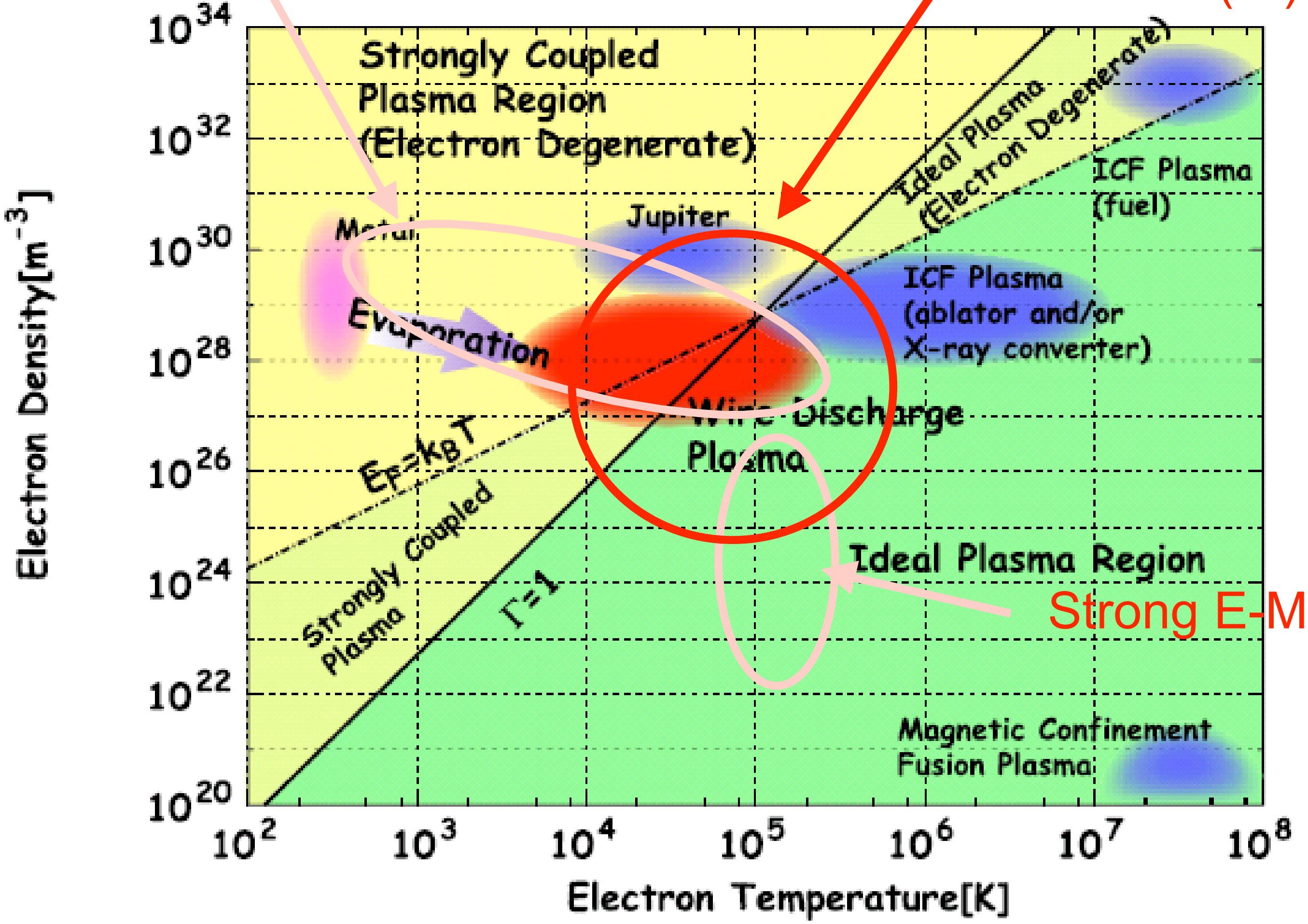
Expected parameter regimes of HED target driven by accelerator (IS) and pulse power devices

Drivers	Induction Synchrotron	Exploding Wires	Pulse-powered Shock Waves
Bunch (Pulse) Length	ns to 10^2ns	10^3ns	$10-10^3$ns
Specific Energy Deposition	10^2-10^5J/g	10^4J/g	10^2eV/particle
Specific Power Deposition	10^7-10^{14}W/g	10^{10}W/g	Quasi-steady state
Achievable Temperature	~ 10^2eV	2-3eV	>10eV
Density	Variable from solid or form to low density with hydrodynamics	Variable from solid to low density with hydrodynamics	10^{17}/cm^3
Geometry	Arbitrary (Cylindrical, Plane, Foils)	Cylindrical and uniform profile	1D and steady state

Expected experimental range of pulse power and accelerator driven HED materials

Wire Discharged Plasma in Water

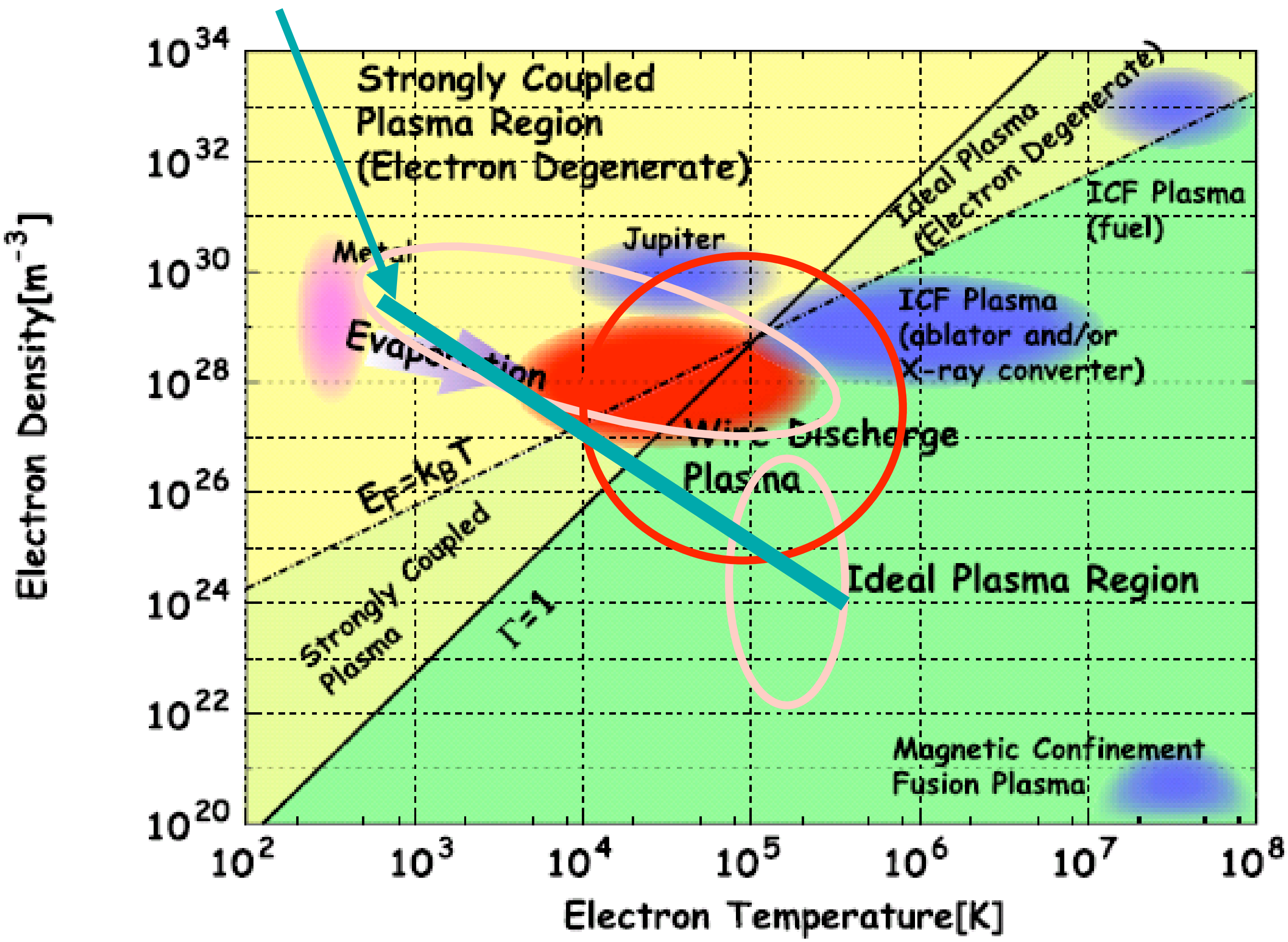
Plasma Target driven by Accelerator (IS)



Strong E-M Shock Waves

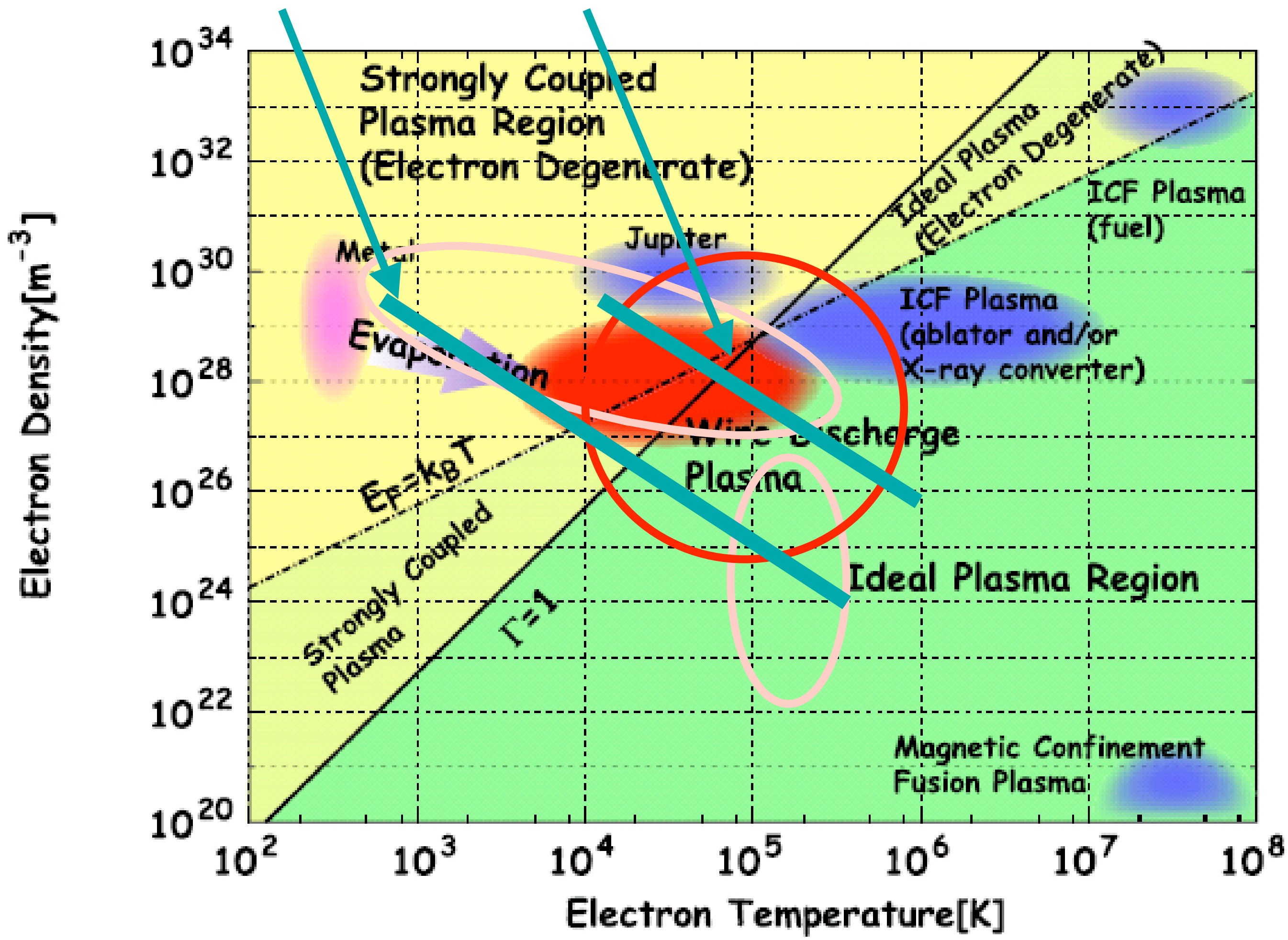
Expected experimental range of pulse power and accelerator driven HED materials

Pulse Power Device

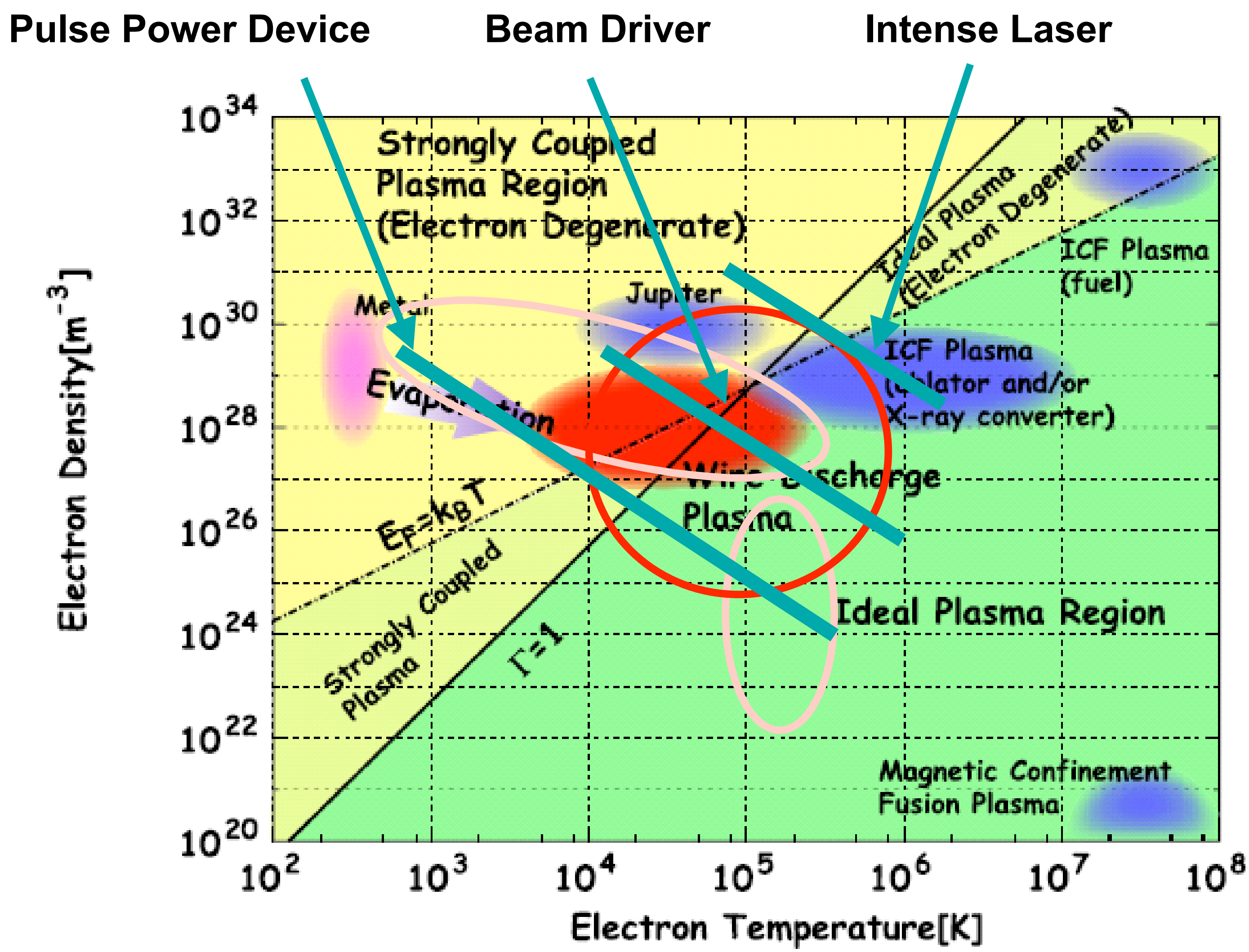


Expected experimental range of pulse power and accelerator driven HED materials

Pulse Power Device **Beam Driver**



Expected experimental range of pulse power and accelerator driven HED materials



Concluding Remarks

- Pulse power and accelerator based driver bring us a well defined, large scale length, and long life sample for HED physics
- Hydrodynamic behaviors driven by the well defined energy deposition profile are useful test problem for EOS models and transport coefficients of materials in a WD state
- Electro-magnetically driven strong, 1-D, QSS shock waves are formed for radiation hydrodynamics
- Induction synchrotron has a possibility to cover extremely wide parameter region in density-temperature plane

- Mutual efforts of pulse-power driven, accelerator driven, and laser irradiated plasma studies are essential to build reliable data base of matters in HED states

Thank you for your attention